

# *Low-Spin States From Decay Studies in the Mass 80 Region*

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Neutron-deficient nuclei in the mass 80 region are known to exhibit strongly deformed ground states deduced mainly from yrast-state properties measured in-beam via heavy-ion fusion-evaporation reactions. Vibrational excitations and non-yrast states as well as their interplay with the observed rotational collectivity have been less studied to date within this mass region. Thus, several  $\beta$ -decay experiments have been performed to populate low-spin states in the neutron-deficient  $^{80,84}\text{Y}$  and  $^{80,84}\text{Sr}$  nuclei. An overview of excited  $0^+$  states in Sr and Kr nuclei is given and conclusions

about shape evolution at low-spins are presented. In general, the non-yrast states in even-even Sr nuclei show mainly vibration-like collectivity which evolves to rotational behavior with increasing spin and decreasing neutron number.

**Key words:** low-spin states; neutron deficient nuclei; prolate deformation.

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## 1. Introduction

There is now extensive experimental evidence for large prolate deformation in the neutron-deficient Rb, Sr, and Y nuclei. For the even-even Sr isotopes, the evidence is based on experimental quadrupole moments extracted from level lifetimes [1,2] and excitation energies of the first excited yrast states [3]. In all these neutron-deficient nuclei, the underlying cause of the prolate deformation has been attributed to the population of strongly polarizing orbitals originating from the  $d_{5/2}$  and/or intruder  $g_{7/2}$  subshells and large gaps in the single-particle level energies.

The evolution of shapes of mass 80 nuclei from near-spherical to  $\gamma$ -soft and to well-deformed shapes as function of particle number and angular momentum has been investigated using different theoretical approaches [4–6]. In some cases, shape coexistence interpretations have been invoked to describe irregularities of the moments

of inertia of some neutron-deficient even-even Se, Kr, and Sr nuclei at low spins [7]. For the even-even Sr isotopes the situation is quite complicated. Large prolate deformations as observed for  $^{76,78}\text{Sr}$  are in agreement with most of the recent calculations while the nucleus  $^{80}\text{Sr}$  is predicted to be spherical in the ground state with  $\beta_2 = 0.053$  [6]. The ground-state deformation of  $\beta_2 \approx 0.4$  as deduced from in-beam  $\gamma$ -ray experiments [1,2] is in contrast to recent results from fast beam laser spectroscopy [8] where the deduced mean charge radii indicate somewhat less deformed shapes for  $^{78,80}\text{Sr}$ . The neutron-deficient even-even Sr isotopes exhibit yrast level sequences (or moments of inertia) at low spins which show large deviations from the behavior expected for a rigid rotor, possibly indicating shape fluctuations. Thus, the issue of the rigidity of the shapes and the occurrence of co-existing configurations are not yet

resolved and have not been thoroughly addressed as many of the key states of interest are of low spins and of non-yrast nature, i.e., they are not well populated in the heavy-ion fusion reactions usually used for the in-beam studies.

Properties of nuclei along the  $N = Z$  line are also of interest for the astrophysically relevant rapid proton capture (rp) process [9] which is thought to be one of the dominant energy sources in cataclysmic binaries like novae and x-ray bursts. The rp process is characterized by a sequence of fast proton capture reactions and subsequent  $\beta$  decay. Usually, the  $\beta$  decay is slow compared to the fast proton capture reactions. Waiting points can develop where the proton capture is compensated by inverse photo-disintegration or where single proton capture is inhibited at the proton-drip line. The lifetimes of these waiting-point nuclei are determined by the  $\beta$  decay of the ground state or thermally excited states. Thus lifetimes of ground states and/or  $\beta$ -decaying isomeric states in the vicinity of the proton-drip line are important input parameters for calculations of nuclear synthesis, luminosity, and time scale [10]. Nucleosynthesis at the extreme temperature and density conditions associated with such events may well proceed beyond the doubly-magic  $^{56}\text{Ni}$  [11].

Only few alternative probes are available for investigating non-yrast states in nuclei far from stability. The most useful is the careful investigation of the  $\beta$  decay from a higher- $Z$  parent nucleus. The parent spins are usually low so a large number of non-yrast states is expected to be populated when the decay energy is large. For a successful  $\beta$ -decay experiment sufficient production of the parent nuclei is needed. Far from stability, this is experimentally difficult as production cross section are small and the nuclei are short-lived.

## 2. Low-Lying Isomers in the Odd-Odd $^{80,84}\text{Y}$ Isotopes

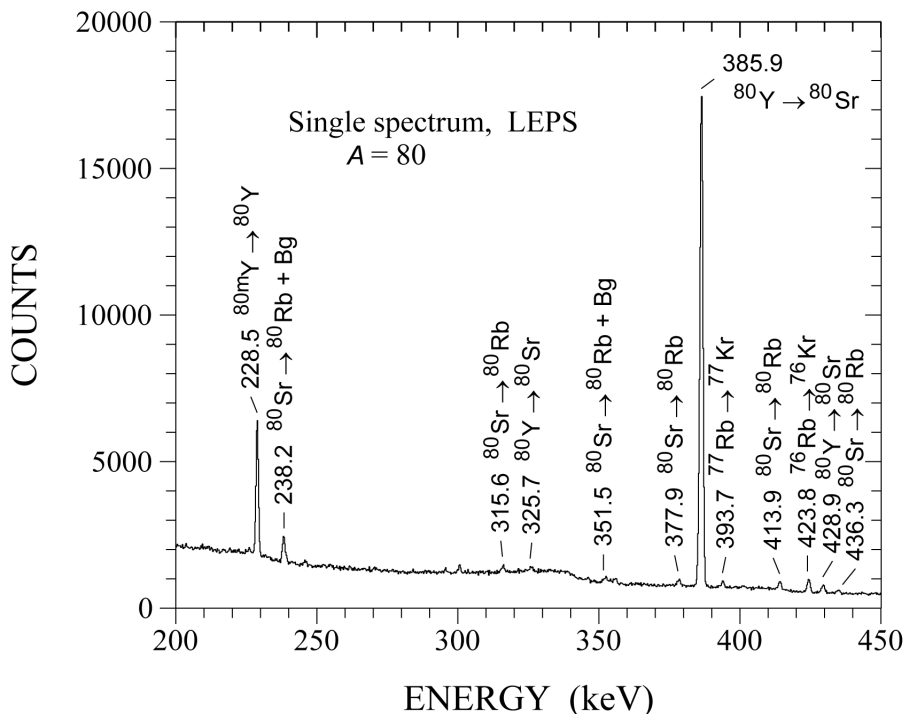
### 2.1 New Isomer in $^{80}\text{Y}$

A new  $\beta$ -decay experiment has been performed to study the low-spin structure of the  $N = Z + 2$  nucleus  $^{80}\text{Y}$ . The  $^{80}\text{Y}$  source has been produced via the fusion-evaporation reaction  $^{24}\text{Mg}(^{58}\text{Ni}, \text{pn})$  reaction at 190 MeV. The use of inverse kinematics provided a strongly forward-peaked recoil spectrum best suitable for an efficient collection and subsequent separation by the Argonne fragment mass analyzer [12]. The  $A = 80$  mass separated recoils were implanted on a plastic tape and transported to a  $\beta$ - and  $\gamma$ -ray counter station consisting of three Ge detectors and a low-energy photon spec-

trometer. Each  $\gamma$ -ray detector had a thin plastic scintillator in front for the detection of  $\beta$  rays. The recoils were implanted within a deposition time of 20 s and their radioactive decay was subsequently measured for 20 s. Several cycles were also performed with 60 s deposition time and 60 s counting time. More experimental details have been reported in Ref. [13].

A single  $\gamma$ -ray spectrum recorded with the low-energy photon spectrometer and representative for the decay of the short-lived mass 80 recoils is displayed in Fig. 1. The strongest  $\gamma$ -ray peak has been identified as the  $2^+ \rightarrow 0^+$  transition in  $^{80}\text{Sr}$ . Further, a new  $\gamma$ -ray transition at 228.5 keV has been found [13] which is the second strongest line in the spectrum. This transition depopulates a new isomer in  $^{80}\text{Y}$  with a half-life of 4.7(3) s [13]. Spin and parity of the isomer has been determined to be  $1^-$ . Thus, the isomer decays by a M3 transition to the  $4^-$  ground state. The extracted M3 transition strength is 0.78(5) Weisskopf units. Most interestingly, the isomer undergoes  $\beta$  decay as well to low-lying states in  $^{80}\text{Sr}$  [14], as can be seen in the decay scheme of the isomer given in Fig. 2, upper left-hand side. This conclusion has been drawn from two experimental facts: (i) The time distribution of the  $2^+ \rightarrow 0^+$  385.9 keV transition in  $^{80}\text{Sr}$  does not show the expected delayed feeding by the 228.5 keV isomeric transition (as the  $4^+ \rightarrow 2^+$  594.8 keV transition does), i.e., the time distribution can be fitted well with a single exponential decay curve. This indicates that the delayed component is canceled out. (ii) The difference spectrum between early and late time correlated events exhibits a strong 385.9 keV transition. This spectrum is shown in Fig. 3. The spectrum has been generated by subtracting the time- $\gamma$  events of the 15 s to 60 s time range (late events) from the time- $\gamma$  events of the 0 s to 10 s range (early events). Further, events in the time range 10 to 15 s have been excluded (see inset of Fig. 3). For normalization, we assumed that the intensity of the 783.1 keV line depopulating the  $6^+$  state at 1763.7 keV in  $^{80}\text{Sr}$  cancels out leading to a factor of 0.68. As a result a small intensity amount of the 594.8 keV line remains in the difference spectrum. This may indicate that the  $1^-$  isomeric  $\beta$  decay is highly fragmented. The situation is similar to the  $1^-$  ground-state  $\beta$  decay of  $^{76}\text{Rb}$  [15]. The difference spectrum indicates, in addition to the strong 385.9 keV transition, a weak 1350.4 keV line. The same 1350.4 keV transition can be seen in the sum coincidence spectrum of the 756 and 1142 keV gates providing evidence for a level at 2492.5 keV. This level seems to be populated in the isomeric decay only and has probably a low spin.

The  $\beta$ -decay branch has been estimated to be about 19(2) %. This result has important consequences for calculations of the rp-process nucleosynthesis of  $^{80}\text{Kr}$



**Fig. 1.** Single  $\gamma$ -ray spectrum recorded with a low-energy photon spectrometer. The mass 80 recoils were mass separated by the Argonne fragment mass analyzer and transported to the counter station by a moving tape system. The figure has been taken from Ref. [13].

since the longer lived ground state of  $^{80}\text{Y}$  ( $T_{1/2} = 30.1(5)$  s [13]) is partly bypassed by the isomeric  $\beta$  decay, and a shorter effective half-life of  $^{80}\text{Y}$  is obtained which leads to a reduction of the calculated overproduction of  $^{80}\text{Kr}$  [10].

Total Routhian surface calculations [4] have shown that the odd-odd nucleus  $^{80}\text{Y}$  exhibits a strongly deformed prolate shape with a quadrupole deformation of  $\beta_2 = 0.37$  for the ground state. The prolate minimum persists up to high rotational frequencies. Thus, the deformed shape inspired the application of two-quasiparticle-plus-rotor calculations to investigate the wave functions of the low-lying states in terms of Nilsson orbitals. We found that the low-spin structure can be well explained if a proton-neutron residual interaction is employed. In this case the ordering of the states and the energy splitting between the  $4^-$  ground state and the  $1^-$  isomer can be well reproduced. The wave functions contain mainly the proton  $[422]5/2^+$  and the neutron  $[301]3/2^-$  Nilsson orbitals. These orbitals are coupled parallel and antiparallel in the  $4^-$  ground state and in the  $1^-$  isomer of  $^{80}\text{Y}$ , respectively. The model calculations demonstrate that the deformed picture accounts very well for the observed properties of the low-lying states in  $^{80}\text{Y}$ .

## 2.2 Low-Spin States in $^{84}\text{Y}$

Early evidence was presented that the odd-odd nucleus  $^{84}\text{Y}$  has very likely an  $1^+$  ground state and a higher-lying ( $5^-$ ) isomer at an energy of about 500 keV [16,17]. This structure was deduced from early decay studies and the excitation energy of the isomer was an estimate only. Also, a few  $\gamma$  rays had been previously assigned to the  $^{84}\text{Zr}$  decay [18], however, not placed into a level scheme. Therefore, three new decay experiments have been carried out: (i) via the irradiation of a  $^{58}\text{Ni}$  target with  $^{28}\text{Si}$  ions at 97 MeV using a modified NORDBALL setup [19], (ii) via the irradiation of a  $^{58}\text{Ni}$  target with 99 MeV  $^{28}\text{Si}$  ions and (iii) via the irradiation of a  $^{58}\text{Ni}$  target with 135 MeV  $^{32}\text{S}$  ions [20]. The latter two experiments were performed at Florida State University. In the first two experiments the chosen target-projectile combinations ensured that the even-even nucleus  $^{84}\text{Zr}$  was produced in-beam, without any in-beam population of states in  $^{84}\text{Y}$  and  $^{84}\text{Sr}$ . In this way all states seen in these two latter nuclei were populated via the  $\beta$ -decay chain  $^{84}\text{Zr} \rightarrow ^{84}\text{Y} \rightarrow ^{84}\text{Sr}$  only. The experiments at Florida State University were carried out with 5 Ge detectors and a low-energy photon spectrometer to detect the  $\gamma$  rays.

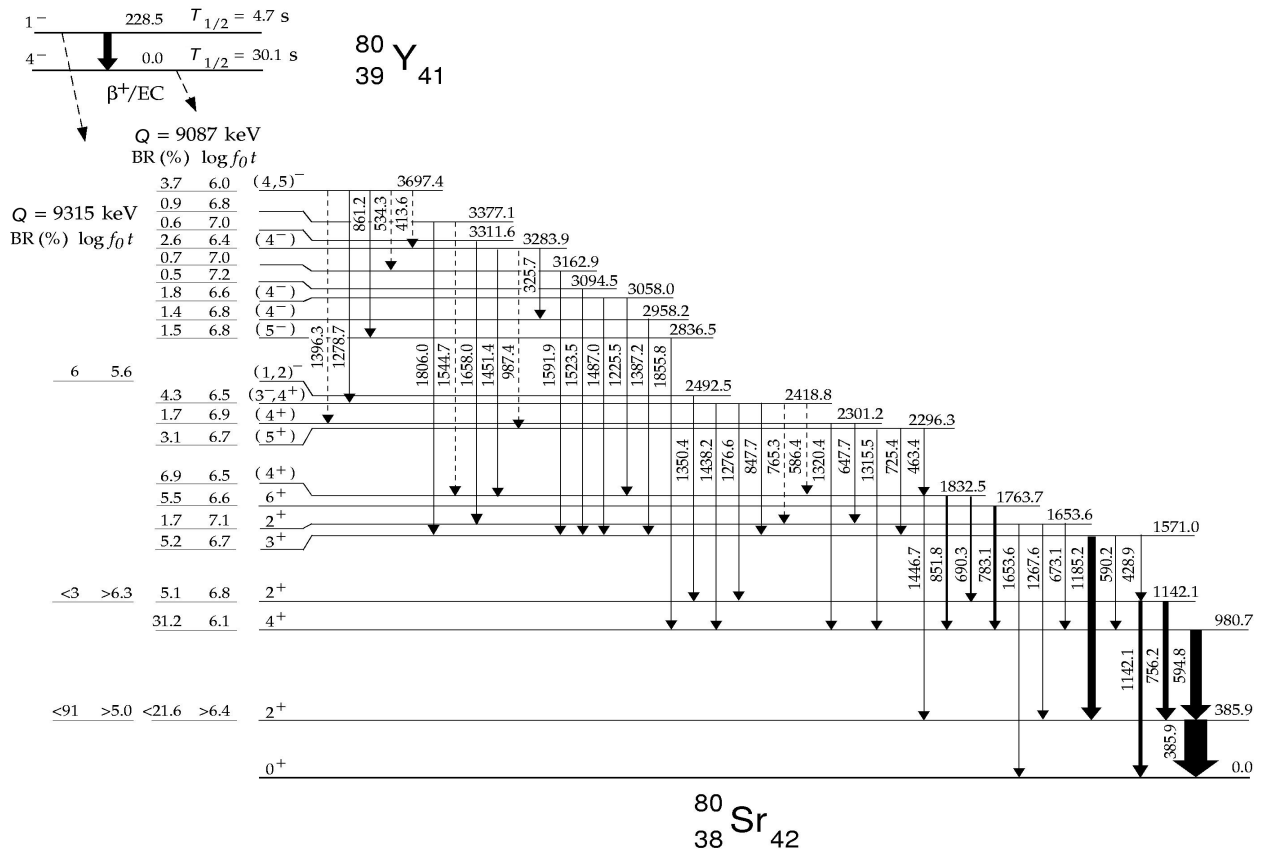


Fig. 2. Level scheme of  $^{80}\text{Sr}$  deduced from the  $\beta$  decay of  $^{80}\text{Y}$ . The figure has been taken from Ref. [14].

It has been found that the  $1^+$  isomer in  $^{84}\text{Y}$  has an excitation energy of 67 keV and undergoes  $\beta$  decay only. No low-energy 67 keV  $\gamma$  transition to the ground state in  $^{84}\text{Y}$  has been seen in the singles spectrum measured with the low-energy photon spectrometer. A partial decay scheme is shown in Fig. 4 where emphasis has been placed on the low-spin structure in  $^{84}\text{Y}$  and the population of the  $0^+$  states in  $^{84}\text{Sr}$  by the  $\beta$  decay of the  $1^+$  isomer. Further, states up to  $(7^+)$  in the  $\gamma$ -vibrational band of  $^{84}\text{Sr}$  have been identified giving evidence for a possible spin and parity assignment of  $6^+$  to the ground state of  $^{84}\text{Y}$ , in contrast to the previous assignment of  $(5^-)$  [17].

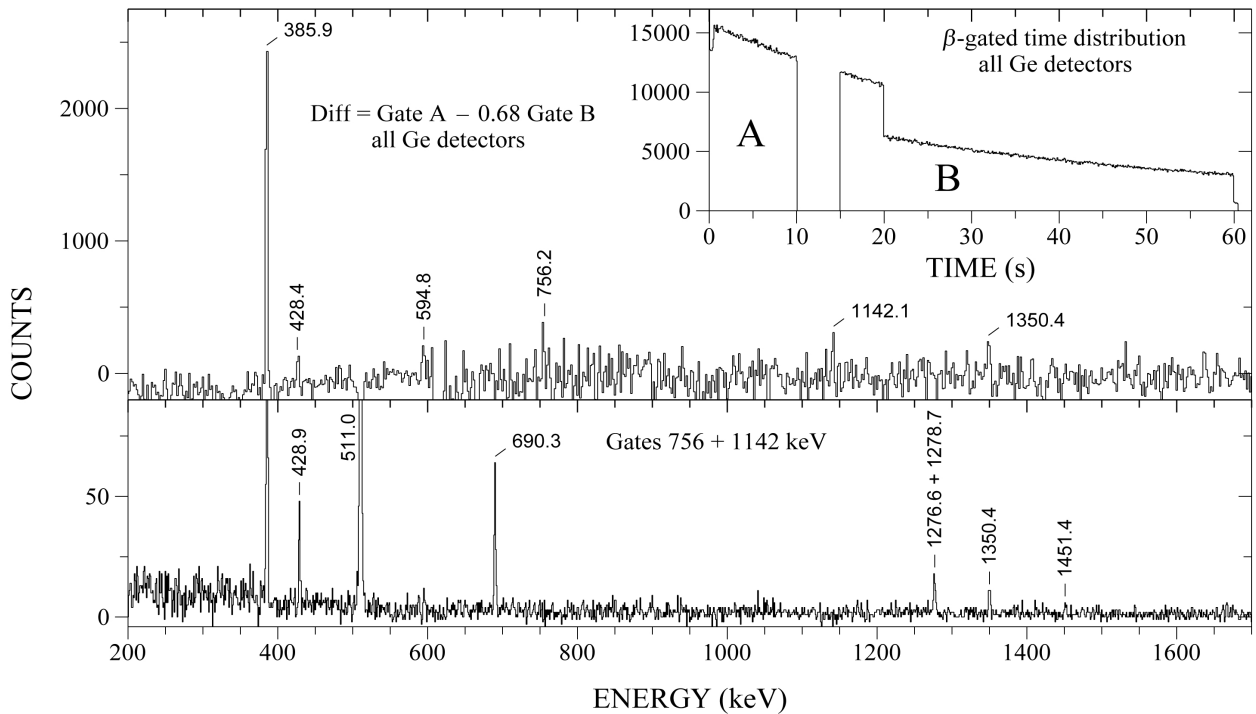
The new decay data revealed many new  $\gamma$  rays in  $^{84}\text{Y}$  and  $^{84}\text{Sr}$  and hence many new levels have been identified in both nuclei. For example, the previously reported excited  $0^+$  states at 1505 and 2075 keV in  $^{84}\text{Sr}$  as identified via a (p,t) reaction [21] have been observed via  $\gamma$ -ray spectroscopy at 1504 and 2072 keV, respectively, for the first time. These states depopulate via 711 and 1279 keV transitions to the first excited  $2^+$  state at 793 keV in  $^{84}\text{Sr}$ . An intense 793 keV peak has been seen only in the coincidence gates at 711 and 1279 keV indicating

a very low multiplicity. Thus the origin is very likely a low-spin state in  $^{84}\text{Y}$ , i.e., the  $\beta$  decay of the  $1^+$  isomer. The number of coincidence events of the 1279 keV line gated by the 793 keV transition in the 10 different detector-pair matrices of experiment (iii) was good enough to deduced angular correlation coefficients [22]. They provide evidence for a  $0^+ \rightarrow 2^+ \rightarrow 0^+$  decay sequence.

### 3. Low-Lying States in Even-Even Neutron-Deficient Sr and Kr Isotopes

#### 3.1 Excited $0^+$ States in Sr Isotopes

The evolution of the nuclear shape from spherical to deformed in the even-even Sr isotopes is well known when moving away from the neutron shell closure at  $N = 50$ . These findings are based mainly on yrast level properties investigated via heavy-ion fusion-evaporation reactions. The study of non-yrast low-lying states may provide additional evidence to support these claims, or may indicate a more complex nuclear structure at low spins. The careful study of the  $\beta$  decay of odd-odd Y



**Fig. 3.** Difference spectrum (top panel) of  $\beta$ -gated events from all Ge detectors to illustrate the decay of the  $1^-$  isomer in  $^{80}\text{Y}$ . The gating conditions are shown in the inset. To obtain the best possible statistics, the events from both 20 s and 60 s cycles have been added up causing the visible step at the time of 20 s. The 756 keV and 1142 keV background-corrected sum coincidence spectrum is shown in the bottom panel. The figure has been taken from Ref. [14].

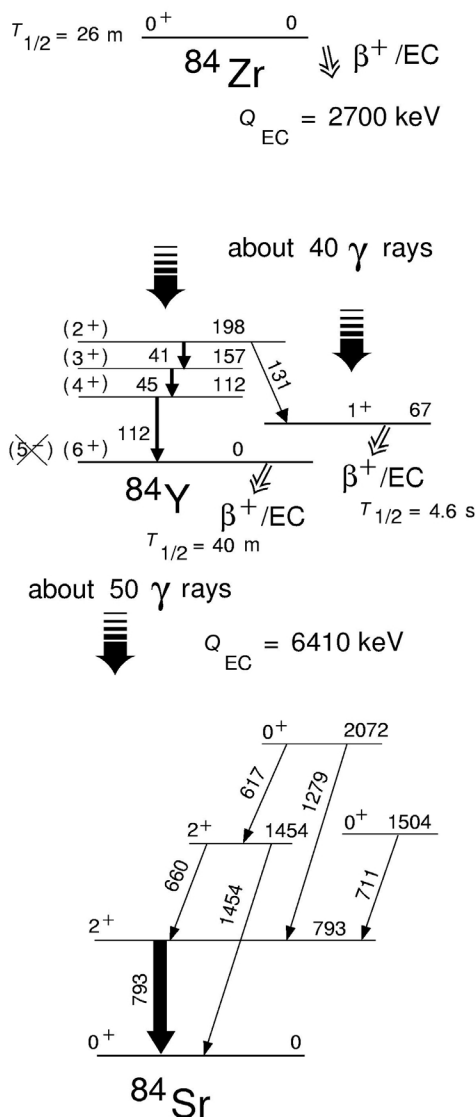
study of the  $\beta$  decay of odd-odd Y nuclei seems to be the best method for populating non-yrast levels in neutron-deficient even-even Sr isotopes. Thus, the experiment described before for the investigation of an isomer in  $^{80}\text{Y}$  has been analyzed for the  $^{80}\text{Y} \rightarrow ^{80}\text{Sr}$   $\beta$  decay as well. The high selectivity of the Argonne fragment mass analyzer and the use of a multi-detector setup provided clean data. The known  $^{80}\text{Sr}$  level scheme could be extended by 14 new levels [14], see Fig. 2. Spin and parity assignments are given based on the observed feeding and depopulation pattern, deduced  $\log ft$  values, and on a comparison with the decay of the  $^{78}\text{Rb}$   $4^-$  isomer to low-lying states in  $^{78}\text{Kr}$  [23].

Most of the known excited  $0^+$  states in mass 80 nuclei have been identified via radioactive decay studies or particle-transfer reactions. The experimental detection is sometimes difficult since a  $0_2^+ \rightarrow 0^+$  E0 transition can be verified only via a conversion electron measurement. Using  $\gamma$ -ray spectroscopy, usually the  $0_2^+ \rightarrow 2_1^+$  E2 transition is detected. In general, the E0 matrix elements depend sensitively on the nuclear charge distribution and thus on the nuclear deformation [24]. Hence, the identification of these excited  $0^+$  states in a chain of isotopes allows to study the evolution of the nuclear shape at low spins. The latest results for the even-even

Sr isotopes ( $Z = 38$ ) are displayed in Fig. 5. The previously reported  $0^+$  states in  $^{84}\text{Sr}$ , detected via particle-transfer reactions and confirmed by present  $\gamma$ -ray spectroscopy, are included. With decreasing neutron number, the position of the excited  $0^+$  states decreases as well and a multiplet-like grouping of the levels is obtained.

### 3.2 Excited $0^+$ States in Kr Isotopes and $N = 38$ Isotones

The systematics of the excited  $0^+$  states in the neutron-deficient even-even Kr isotopes is plotted in Fig. 6. The recently discovered low-lying  $0_2^+$  state in  $^{74}\text{Kr}$ , at most 85 keV above the first excited  $2^+$  state at 456 keV [25], refines the previously suggested shape coexistence picture [26]. This picture of a deformed-spherical shape coexistence was invoked to explain the irregularities in the energy spacings (or moments of inertias) of the lowest yrast excitations in the even-even  $^{74,76}\text{Kr}$  nuclei. Now an oblate shape is suggested for the excited  $0^+$  state in  $^{74}\text{Kr}$ , in contrast to the prolate deformed ground-state band. The half-life reported for the  $0_2^+$  in  $^{74}\text{Kr}$  is the partial time for the E0 transition. The low-energy  $\gamma$ -ray decay has not been found yet.



**Fig. 4.** Selected low-lying states in odd-odd  $^{84}\text{Y}$  and even-even  $^{84}\text{Sr}$  observed in  $\beta$  decay via the chain  $^{84}\text{Zr} \rightarrow ^{84}\text{Y} \rightarrow ^{84}\text{Sr}$  using five Ge detectors and a low-energy photon spectrometer. The experimental results have been taken from Refs. [19,20].

It should be pointed out that the second  $0^+$  state in  $^{74}\text{Kr}$  fits quite well into the  $N = 38$  systematics as can be seen in Fig. 7. In most of these isotones, an excited  $0^+$  state has been found which decays by a low-energy  $\gamma$  ray to the first  $2^+$  state. The deduced  $0_2^+ \rightarrow 2^+$  E2 transition strengths are in the order of 45 Weisskopf units indicating substantial collectivity. The reported E0 matrix elements are also given in the figure.

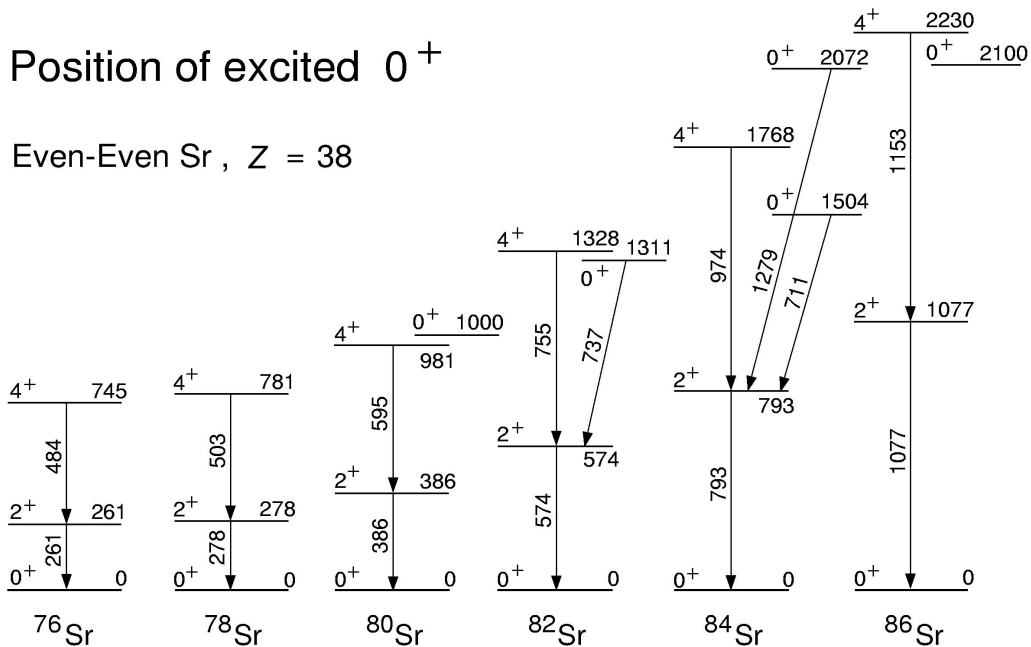
### 3.3 Vibration-Like Multiplets in Even-Even Sr Nuclei

As can be seen in Fig. 8, the new level scheme of  $^{80}\text{Sr}$  deduced from our  $\beta$ -decay study is clustered into states typical of one-, two-, and three-phonon multiplets of an anharmonic vibrational nucleus. In this approach the lowest  $2^+$  state at 385.9 keV can be interpreted as an one-phonon vibrational state. States corresponding to the two-phonon triplet may be the observed states with spins  $2_2^+$  and  $4_1^+$  at energies of 1142.1 and 980.7 keV, respectively. From theoretical considerations there should also be a  $0^+$  state to complete the two-phonon triplet. A  $0^+$  level at 1.0 MeV was observed in a  $^{78}\text{Kr}(^3\text{He}, n)^{80}\text{Sr}$  reaction study [29] but this level has not been seen in our decay data set. Based on a phenomenological parametrization of the effective interaction between phonons [30,31] and using experimental values for the interaction parameters as deduced from members of the observed three-phonon multiplet, a range of 820 keV to 880 keV can be estimated for the excitation energy of the two-phonon  $0^+$  state. For three phonons, the expected multiplet of levels consists of  $0_3^+$ ,  $2_3^+$ ,  $3_1^+$ ,  $4_2^+$ , and  $6_1^+$ . There are observed states with  $2_3^+$ ,  $3_1^+$ ,  $4_2^+$ , and  $6_1^+$  at 1653.6 keV, 1571.0 keV, 1832.5 keV, and 1763.7 keV, respectively, which might be identified with these excitations. The expected  $0_3^+$  level has not been seen. Similar to the estimate of the excitation energy of the  $0_2^+$  state, an energy range of 1890 keV to 2270 keV can be deduced for the third  $0^+$  state based on the anharmonicity of the  $2_2^+$  state.

The observed vibrations in  $^{80}\text{Sr}$  are clearly anharmonic since the  $(2I + 1)$  weighted energy centroids of the known members of the multiplets are at 1036 keV and 1726 keV for  $n = 2$  and 3, respectively, i.e., the higher orders (with  $n = 2, 3$ ) are not strictly a multiple of the one-phonon energy of 386 keV. The deviations from the expected energies for a harmonic vibrator can be attributed to various anharmonic effects. One such anharmonicity may arise from a finite quadrupole deformation or angular momentum dependence of the nuclear shape. Much less anharmonicity is needed to understand the low-lying states in  $^{84}\text{Sr}$ , as can be seen on the right-hand side of Fig. 8. In particular, the observed  $0^+$  states fit very well into this interpretation and complete the multiplets. The energy centroids of the  $n = 2, 3$  multiplets are almost a multiple of the 793 keV ( $n = 1$ ) energy. Thus, an almost harmonic vibration-like nature in  $^{84}\text{Sr}$  is deduced.

## Position of excited $0^+$

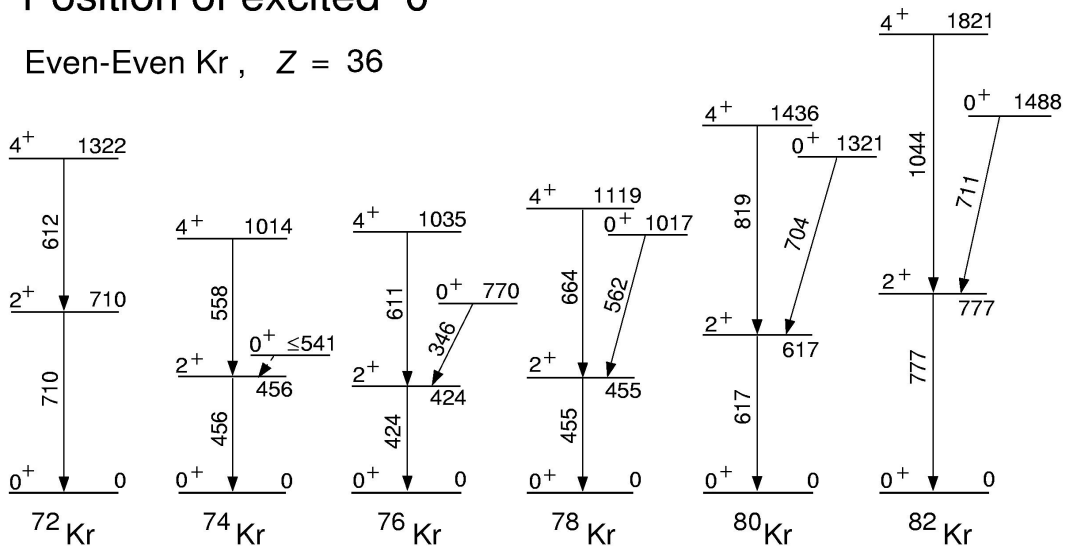
Even-Even Sr,  $Z = 38$



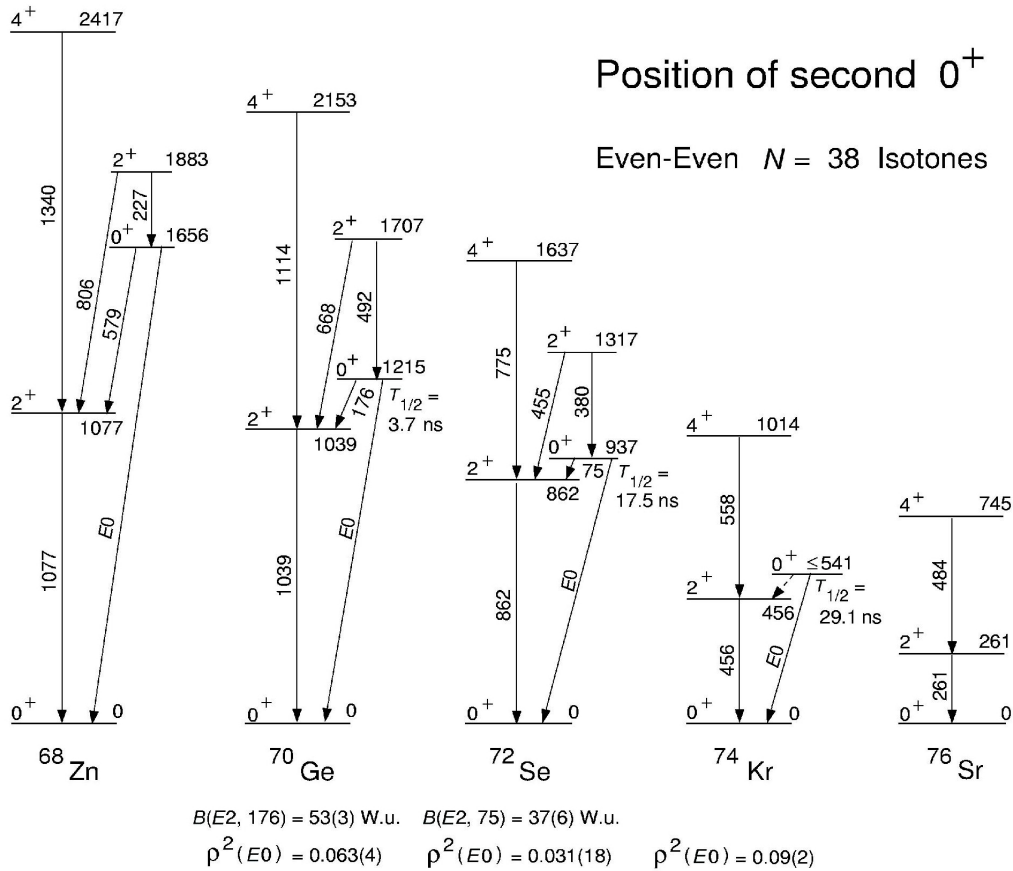
**Fig. 5.** Excited  $0^+$  states and the lowest yrast excitations are displayed for even-even neutron-deficient Sr isotopes. The experimental results on the  $0^+$  states have been taken from:  $^{80}\text{Sr}$ , Ref. [29];  $^{82}\text{Sr}$ , Ref. [17];  $^{84}\text{Sr}$ , Refs. [20,21];  $^{86}\text{Sr}$ , Ref. [21].

## Position of excited $0^+$

Even-Even Kr,  $Z = 36$



**Fig. 6.** Excited  $0^+$  states and the lowest yrast excitations are displayed for even-even neutron-deficient Kr isotopes. The experimental results on the  $0^+$  states have been taken from:  $^{74}\text{Kr}$ , Ref. [25];  $^{76,78,80,82}\text{Kr}$ , Ref. [17].

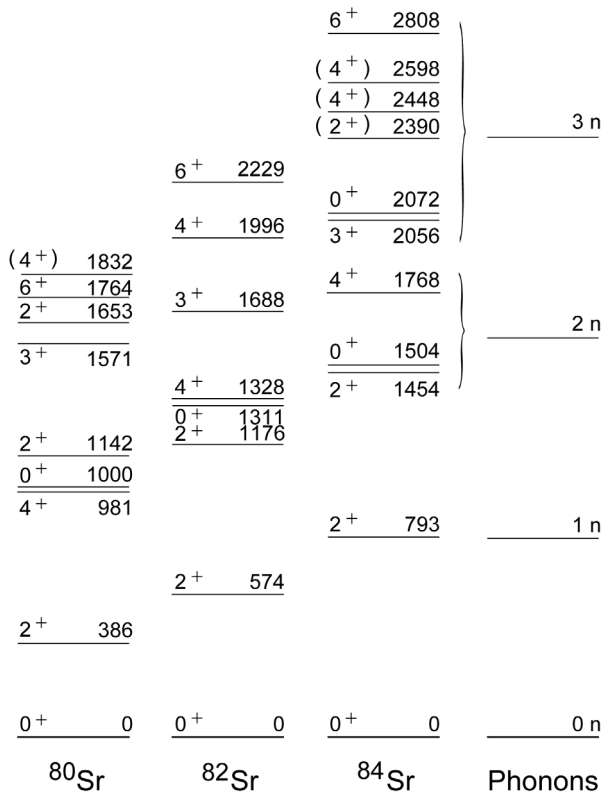


**Fig. 7.** Excited  $0^+$  states in some neutron-deficient  $N = 38$  isotones. The experimental  $E2$  and  $E0$  transition strengths are given. The data have been taken from:  $^{70}\text{Ge}$ , Ref. [27];  $^{72}\text{Se}$ , Ref. [28];  $^{74}\text{Kr}$ , Ref. [25].

## 4. Summary and Conclusions

Modern  $\beta$ -decay experiments employing multi-Ge detector and scintillator arrays combined with in-flight mass separation of recoils produced via nuclear reactions provide a very sensitive tool for the investigation of low-spin states in nuclei far off the line of stability. This has been demonstrated by the recent results obtained for the highly-fragmented radioactive decay of  $^{80}\text{Y} \rightarrow ^{80}\text{Sr}$ . In general, the new decay data suggest that the low-lying structures of  $^{80,84}\text{Sr}$  show many vibration-like features in a potential with modest deformation including candidates for two- and three-phonon multiplets. This vibration-like nature seems to evolve to a more rotational behavior with increasing angular momentum and decreasing neutron number.





**Fig. 8.** Low-lying levels in the even-even  $^{80,82,84}\text{Sr}$  isotopes. The level energies indicate the vibration-like multiplet structure. For  $^{84}\text{Sr}$ , the multiple one-phonon energies are given on the right-hand side.

## Acknowledgments

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